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Final Technical Report

Downhole Heater Cables for Oil Shale Recovery

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Final Report

Downhole Heater Cables for Oil Shale Recovery

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1 Executive Summary

Due to the increased global demand for petroleum, the cost of oil has recently reached prices in excess of $140 per barrel. As the worldwide demand for oil continues to grow, it is estimated that the industry will need to produce an additional 100 million barrels/day by 2015 to meet the projected rate of consumption. One potential source of additional petroleum is oil recovered from oil shale. Approximately two-thirds of the world's oil shale deposits are located in the Green River shale deposits in Colorado, Wyoming, and Utah. For many years, the relatively low price of oil available in the international marketplace made recovery of oil from shale economically unfeasible. Recently, however, the use of in-situ oil shale recovery has been evaluated as a possible means of extracting this resource. In this process, thermoelectric heaters are installed into underground formations to heat the oil in place. This heating process converts the kerogen to an oil-like fluid that can be pumped to the surface and refined using conventional processes.

The overall goal of this U.S. Department of Energy Small Business Innovative Research (SBIR) program was to develop and demonstrate heater cables for use in in-situ oil shale recovery applications. A key technological challenge was designing the electrical insulation to operate reliably in the downhole environment. For oil shale recovery, a composite insulation was applied onto the conductor using a ceramic-fiber tape that is pre-impregnated with pre-ceramic polymeric resin (i.e., prepreg). After wrapping, the insulation is heated to 150°C to "green-stage" the material. At this point in the process the insulation is mechanically robust and electrically insulating. The ceramic insulation is obtained by heating the green-staged insulation to temperatures in excess of 500°C. Obtaining the ceramic state can be accomplished either prior to installation, or by using the heater to convert the material after deployment.

The results of this work showed that an innovative ceramic-composite electrical insulation material can meet the requirements for oil-shale recovery, while also being produced using industrially-viable manufacturing processes. Key accomplishments of this work included:

- Demonstrating high-performance NANUQ™ heater with low leakage current and high electrical resistivity characteristics at elevated temperatures.
- Characterizing the mechanical performance of the heater insulations.
- Fabricating prototype heaters using a readily scalable, prepreg insulation process.
- Completing more than 5,000 hours of continuous testing at temperatures ranging from 760 to 850°C and applied voltages ranging from 350 to 1000 VAC.
- Evaluating the engineering trade-offs associated with heater design and downhole deployment.

In addition to oil-shale recovery, the technology developed in this SBIR program also has important implications for other energy-related applications, including potential use in Enhanced Oil Recovery (EOR), Geothermic Fuel Cells, and Geothermal energy production. The following report summarizes the results of this work and CTD's plans to transition this technology into the commercial marketplace.

2 Introduction

This report documents the technical progress achieved by Composite Technology Development, Inc. (CTD) on SBIR Grant DE-FG02-05ER84198, entitled "Downhole Heater Cables for Oil Shale Recovery." This report is submitted to the Department of Energy (DOE) in partial fulfillment of grant requirements. It is not intended for release outside the U. S. Government.

2.1 Background

Due to the increased global demand for petroleum, the cost of oil has recently reached prices in excess of $140 per barrel. As the worldwide demand for oil continues to grow, it is estimated that the industry will need to produce an additional 100 million barrels/day by 2015 to meet the projected rate of consumption. Very few new oil field discoveries have been made since the 1970's, and as a result there is a growing concern that there will be a production shortfall much sooner than previously anticipated [1,2,3,4].

One potential source of additional petroleum is oil recovered from oil shale. Worldwide reserves of oil shale are estimated at 3.7 trillion barrels, or a supply that is 40 percent larger than the remaining conventional global supply of petroleum. Two-thirds of this oil shale is thought to be located in the western United States [1]. At this time, the U.S. produces only a small fraction of the oil it consumes and is heavily reliant on foreign sources. The ability to cost-effectively obtain this resource locally would reduce the nation's dependence on foreign governments and provide the U.S. economy with a secure, reliable source of petroleum. To address this opportunity, the President's 2007 Federal budget proposal included an additional $3.3M for the Bureau of Land Management oil shale research and development leasing program.

The United States' need for a cost-effective oil shale industry was described in a recent Department of Energy report [1]. That document outlines the need for developing alternative sources of petroleum fuels to offset the growing international demand for oil. It is estimated that a fully developed oil shale industry could eventually become a $1-trillion-per-year domestic industry by 2020. Perhaps more importantly, this industry would provide a secure source of petroleum products for U.S. consumers and businesses. This would directly benefit the automotive, shipping, and travel industries, while simultaneously helping to ensure the nation's energy security. Thus, a significant business opportunity exists for both the producers of oil shale and the developers of technology to support this emerging industry.

2.2 Description of Oil Shale Recovery Process

Oil shales are fine-grained sedimentary rocks containing relatively large amounts of organic matter. The organic material is an insoluble substance referred to as kerogen, and the shale is actually a hard rock (marl). Because it is insoluble, the kerogen must be thermally separated from the rock. Once separated, the kerogen can be converted into a petroleum-like substance at high temperatures. The resulting material can then be refined using well-established processes.

It is estimated that approximately two-thirds of the world's oil shale deposits are located in the Green River shale deposits in Colorado, Wyoming, and Utah. For many years, the relatively low price of oil available in the international marketplace made recovery of oil from shale economically unfeasible. However, the need for efficient methods of extracting oil shale has been re-evaluated because of the ever-increasing global demand for oil.

Two primary methods have been used to obtain oil from shale. The first process involved mining the oil shale and heating the kerogen-containing rocks to elevated temperatures. This process, known as retorting, was found to be economically inefficient because of the high cost of mining the oil shale and the relatively low yield of the process. For example, Unocal operated the last large-scale experimental mining and retorting facility in the western United States from 1980 until 1991. At this site, Unocal produced 4.5 million barrels of oil from oil shale, but only extracted 34 gallons of oil per ton of rock [2].

Large-scale mining and subsequent surface processing of the oil shale also has a negative environmental impact that must be considered. The establishment of open pit mines would create a site that will be difficult to re-vegetate once the location is closed to oil shale recovery. Thus, the environmental impact and site reclamation costs must also be added to the already costly and inefficient mining process.

An alternative process to mining is called "in-situ retorting" [5,6]. In this process (Fig. 1), holes are bored deep into the underground shale deposits, and heaters are placed into the holes. When heated to temperatures on the order of 760 to 850°C, the shale becomes hot enough for the kerogen to be converted to oil in place. This process eliminates the shale mining costs and allows the newly formed oil to be pumped directly to the surface. Once at the surface, the oil may be refined using conventional facilities. In addition to being more cost-effective, this procedure is also more environmentally benign because it eliminates the need to dispose of the mined shale once the oil has been extracted.

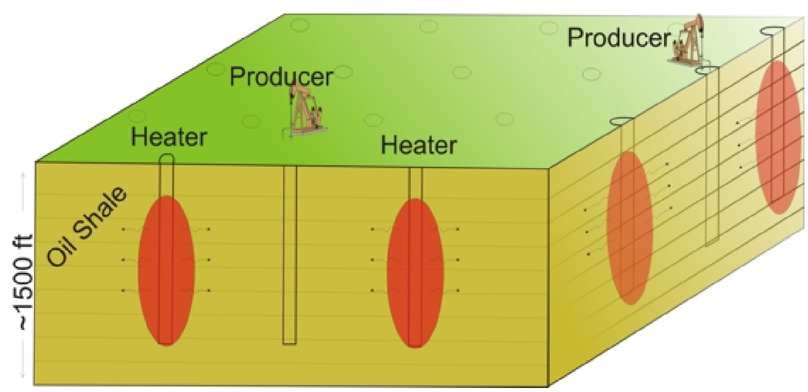

Figure 1. In-situ oil shale recovery process.

2.3 Downhole Heater Performance Requirements

Electrical heater cables capable of long-term operation at 760 to 850ºC (1400 to 1550ºF) are needed to enable the recovery of oil from depths on the order of 600 to 1500 meters (2000-5000 feet). As seen in Figure 2, a typical heater element is a 1.2 to 2.5-cm diameter conductor, surrounded by an inorganic insulation and an outer stainless steel sheath.

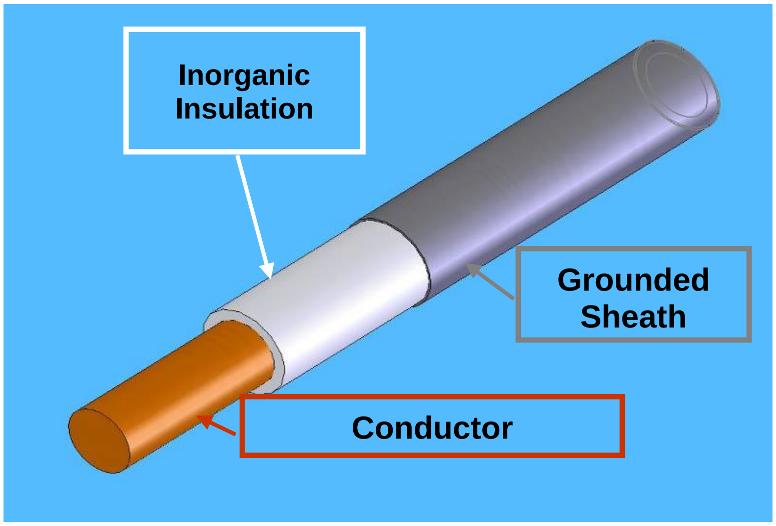

Figure 2. Downhole heater cable schematic.

Today, the most commonly used high-temperature heaters are Mineral Insulated (MI) cables. Existing MI cables use a particulate magnesium oxide (MgO) layer to electrically isolate the conductor from the outer sheath. For oil shale recovery applications, a significant concern is the mobility of the conductor within the packed-powder insulation. The MgO powder was specifically selected for this process because its flow characteristics enable the use of a swaging process to produce the cables. In practice, this particulate flow causes the insulation thickness to vary along the length of the cable, and can easily lead to conductor-to-sheath electrical shorts when the cable is bent or subjected to compressive or crushing loads.

Similarly, an undesirable redistribution of the powder insulation can also be caused by shifts in the underground rock formations. In this instance, the application of compressive forces can cause the insulation to shift and the sheath to collapse, thus creating an electrical short in the heater and rendering it unusable.

Another limitation of MI-insulated cables for in-situ oil shale recovery is the susceptibility of the mineral insulation to moisture-induced performance degradation. MgO is well known to be hydroscopic and under high-temperature, high-voltage conditions the presence of moisture can cause degradation in insulation performance over time. For this reason, manufacturers of MI cables typically limit their maximum operating temperature to 250ºC, far below what is needed for oil shale recovery [7].

Thus, the heater cables for this application require insulation materials with high-temperature stability, moisture resistance, high dielectric strength, and mechanical durability, which is a combination of properties not currently available in the marketplace. Table 1 summarizes the operational requirements for downhole heaters that have been established to date.

Table 1. Performance Requirements for Downhole Heater Cables

Performance Characteristic	Design Requirement
Operational temperature	760 to 850ºC (1400 to 1550ºF)
Environment	Marine environment (steam, H_2S, CO_2, oil)
Voltage	600 VAC, eventually to > 4,000 VAC
Cable length	300 to 1,500 meters (1,000 to 5,000 feet)
Lifetime	>100,000 hours (>11.5 years)
Heater position in cable	Uniform insulation thickness around conductor

3 SBIR Program and Technical Results

Over the course of this program, CTD developed and demonstrated a new class of high-temperature, downhole heaters for use in in-situ oil-shale recovery processes. These heaters are based on a novel, ceramic-composite insulation that enables long-term, high-voltage operation at elevated temperatures. The following sections provide a detailed description of the work performed in the Phase I and Phase II programs.

3.1 Optimization and Testing of Composite Insulation Materials

Fabrication of Insulation Test Articles

In this task, prepreg ceramic insulation was prepared for use in the fabrication of heater segments. Initially, this work involved the fabrication and testing of flat-plate laminates produced by consolidating impregnated tapes under temperature and pressure. As seen in Figure 3, the prepreg tape was consolidated under pressure and then cured at 150°C to produce "green-state" composites with nominal fiber volume fractions of 50%. At this point in the process, the composite is mechanically robust and can be readily handled or machined. Next, the composite is heated at temperatures in excess of 500°C to convert the pre-ceramic polymer to a ceramic material. Laminates were produced with nominal thicknesses of 3.2 and 0.5 mm for use in mechanical and through-thickness electrical tests, respectively. Both green- and ceramic-state materials were produced in this work.

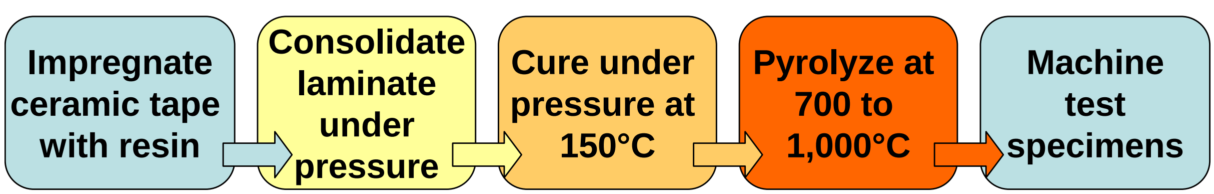

Figure 3. Process flow for the production of ceramic matrix composite insulation.

The thermal processing conditions needed to produce the ceramic-state material were identified by thermo-gravimetric analysis (TGA). This procedure is used to measure weight loss in materials upon heating to elevated temperatures. As seen in Figure 4, the CTD-1202 resin is converted to a ceramic between 400 and 600°C. The weight loss is due to the evolution of small quantities of CO_2 and H_2O. As these species are evolved, the inorganic polymer is converted to a silica-based ceramic with a high electrical resistivity. The pre-ceramic resin system used in this work was previously designed by CTD to produce a high ceramic yield for use as an insulator for high-field magnets [8].

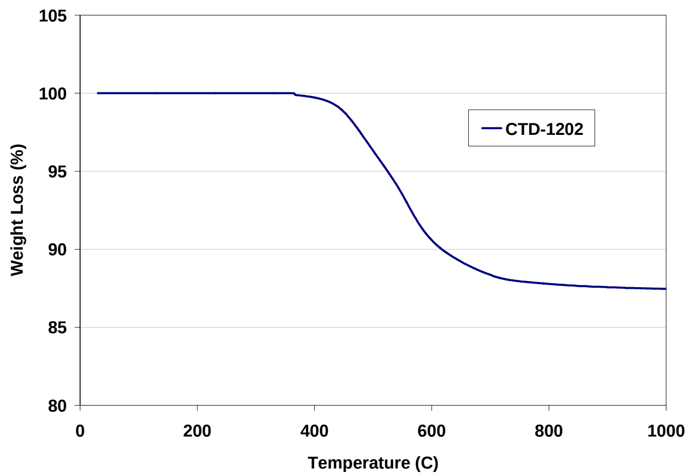

Figure 4. TGA data for CTD-1202 in air.

Based on this data, ceramic composite laminates were pyrolyzed at temperatures ranging from 700 to 1000°C to assess the performance of the insulation processed at different temperatures. Weight measurements of the laminates pyrolyzed at these various temperatures showed no significant differences due to the peak processing temperature used to produce these parts.

Evaluation of Green- and Ceramic-State Insulations

In this work, the physical properties of the green and ceramic insulation were characterized at 25°C. This included measurement of the density, mechanical strength, and dielectric breakdown strength. All of the tests performed in this investigation were based on the relevant ASTM standards for characterizing the performance of composite materials.

As seen in Table 2, the density of the insulation is found to increase after heating to elevated temperatures. Additionally, the dielectric breakdown strength of the material increases by ~15% after conversion from the green to ceramic state. While the density and electrical performance improve after pyrolysis, the mechanical properties of the green-state insulation are significantly higher than those of the ceramic-state material. In addition to its higher strength, the green-state material also exhibits an elastic behavior that will better enable the spooling and handling of cables. The elastic nature of the green state insulation is shown in Figure 5. In this instance, a green-state insulation specimen with dimensions of 2.8 x 0.64-cm x 3.2-mm was tested using a 3-point loading method. As the crosshead travel increased, the specimen deformed under the increasing load. However, the part did not exhibit a mechanical failure and when the load was released the specimen returned to its original rectangular geometry.

Table 2. Properties of Green-State and Pyrolyzed Insulation at 25°C

Property	Units	CTD-1202 Green-Staged at 150°C	CTD-1202 Air-Pyrolyzed at 1,000°C
Apparent Density	g/cc	2.1	2.5
Dielectric Breakdown Strength	kV/mm	19.7	23.5
Dielectric Breakdown Constant	$kV/mm^{1/2}$	15.0	18.0
Compression Strength	MPa	281.0	60
Compression Modulus	MPa	2770.0	400
Young's Modulus	GPa	65.8	11.7
Apparent Shear Strength	kPa	3058.0	368.5
Apparent Flexural Modulus	MPa	356.4	117.8

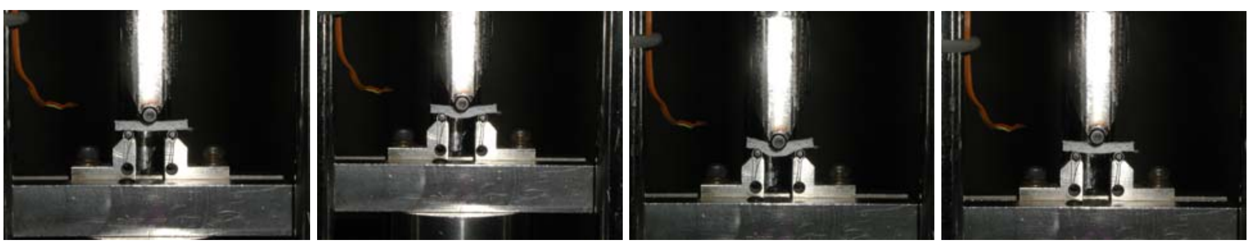

Figure 5. Photographs showing the elastic behavior of the green-state insulation.

Based on the above results and anticipated heater-deployment scenarios, there are several manufacturing and handling advantages that can be gained by producing and distributing heaters with green-state insulation. In this condition, the material has superior mechanical performance and can be readily handled and deployed into the downhole environment. Once in place, the heater can be activated, to start the process of heating the surrounding environment (rock), as well as to convert the insulation to the ceramic state. After conversion, the higher density and improved electrical performance provide for the long-term, high-temperature, high-voltage operation needed for oil shale recovery.

3.2 Fabrication of Downhole Heaters

In this work, prepreg ceramic-composite insulations were applied to conductors and cured to produce green- and ceramic-state components. Additionally, metal sheaths were applied over the insulation to complete the assembly process. The following sections describe the procedures used throughout this program to develop high-temperature heaters.

Production and Application of Ceramic-Based Insulation

The first step in heater manufacture was the production of ceramic prepreg. As seen in Figure 6, CTD-1202 pre-ceramic resin was applied to 5.4-cm wide ceramic tape using a CD-8048 laboratory-scale impregnation machine. In this process, the dry tape is passed through a resin bath (not shown), and the resin content is controlled using nip rollers. Next, the impregnated tape travels through an oven to advance (or “B-stage”) the resin. Finally, the impregnated tape is wound onto a spool similar to that seen on the front end of the prepreg machine.

Figure 6. Continuous production of pre-ceramic prepreg insulation.

Once the prepreg was produced, heater cable segments were fabricated by wrapping the prepreg insulation onto stainless steel rods. In this work, 1.9-cm (0.75-inch) diameter rods were wrapped to produce specimens with 0.317-cm (0.125-inch) insulation. This produced a heater element with a nominal diameter of 2.54 cm (1 inch). Insulated rods up to 46 cm (18 inches) in length were produced for testing purposes.

As seen in Figure 7, the prepreg tape was applied with 50 percent overwrapped insulation. That is, the insulation was overwrapped at one-half the width of the prepreg ceramic tape as it was applied to the conductor. The image to the left shows the application of the prepreg insulation system. After the insulation was applied, the assembly was wrapped with shrink tape to place the prepreg material in compression. The assembly was then heated to 150°C to cure the resin. The right-hand photograph in Figure 7 shows a typical, green-staged heater segment produced in this program. After the green-staging process, the insulation is converted to a ceramic by heating to peak temperatures on the order of 1000ºC.

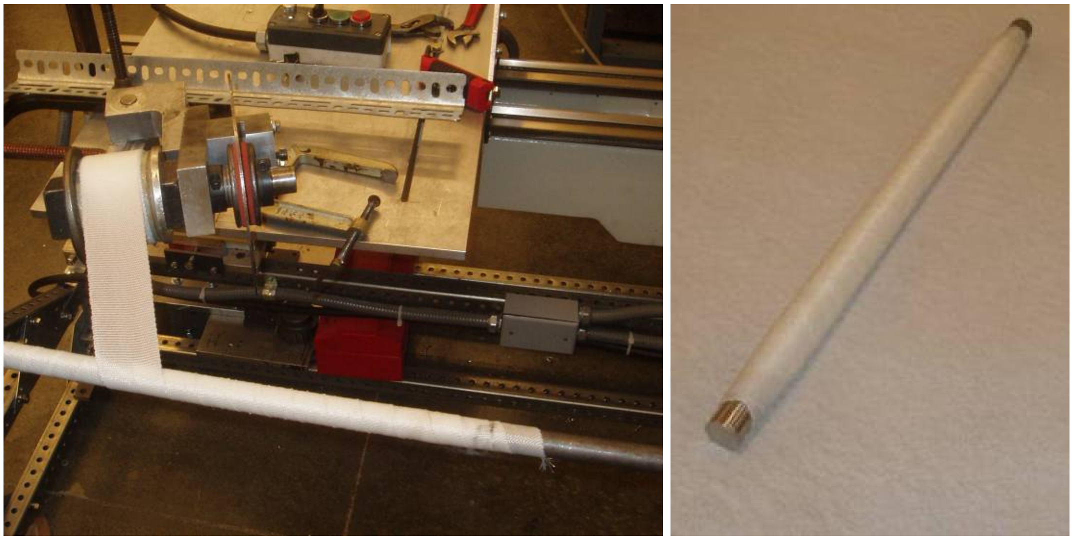

Figure 7. Photographs showing the production of heater length using a prepreg ceramic tape (left) and a green-staged heater segment (right).

It should be mentioned that relatively short specimens were produced to accommodate the high-temperature electrical characterization facility used in this work. In practice, the quantity of prepreg tape produced, as well as the process used for continuous application of the tape to the conductor, are readily scalable to meet the anticipated demand for these heaters. Moreover, the wrappable insulation can be applied to any diameter of conductor and at any thickness. These materials and processes were chosen to ensure the rapid transition of this process to the production of long-length heater cables.

Installation of Stainless Steel Sheaths

The second step of the heater manufacturing process is to install stainless steel sheaths over the insulation. This provides an electrical ground for use in high-temperature leakage current testing of the NANUQ™ heaters. Two methods of sheath application were used in this work. Those included (1) sliding a stainless steel pipe over the insulation and (2) welding a clamshell sheath onto the insulation. Both of these methods were used to apply sheaths onto green-state and ceramic insulation. In the case of the green-state insulation, the sheath was applied and the assembly was heated to 1000°C to produce the ceramic phase. Subsequent testing indicated that the dielectric breakdown strength of the heater insulation processed in this manner is the same as that obtained by pyrolyzing the insulation first and applying the sheath after the ceramic conversion.

Another important outcome of this work was the verification that the green-state insulation could withstand the welding temperatures associated with the application of the sheath. Not only was this important for sheathing, but for the downhole deployment of these heaters. It is likely that lengths of cable will have to be joined at the well head, and this may be accomplished by welding. Thus, the results of this task demonstrated that both the green-state and ceramic forms of the insulation are compatible with the joining methods that will be used in the field.

Figure 8 shows an example of the welding process, as well as a finished part that was produced in this investigation. The image to the left also shows thermocouples that were embedded in a test article to determine the temperature rise in the insulation due to the application of the welding torch. In this example, a peak temperature of 350ºC was observed in green-state insulation over a time interval of only a few seconds. The photograph to the right shows a part that was pyrolyzed at 1000ºC after the sheath was welded over the insulation.

Figure 8. Photographs showing the welding of a sheath onto green insulation (left) and a heater segment that was pyrolyzed at 1000ºC after the sheath was welded over green-state insulation.

3.3 Electrical Characterization of Insulation Materials

High-Temperature Electrical Testing of Heater Segments

After the manufacturing process was optimized, the electrical properties of prototype parts were tested at a commercial facility. In those tests, the leakage current was measured at temperatures ranging from 760 to 870ºC (1400 to 1600ºF), and at applied voltages ranging from 400 to 1000 VAC. In this procedure, the specimen was heated in an oven to the specified temperature and the voltage was incrementally increased at periodic intervals. After each voltage increase, the leakage current was allowed to stabilize before it was further increased. As seen in Figure 9, the leakage current values for CTD’s composite insulation stabilizes at a value on the order of 0.4 to 0.8 mA/ft. While the data in Figure 9 shows results through ~900 hours of testing, this specimen completed more than 5,000 hours of continuous testing, with a maximum leakage current of 0.8 mA/ft observed during this time.

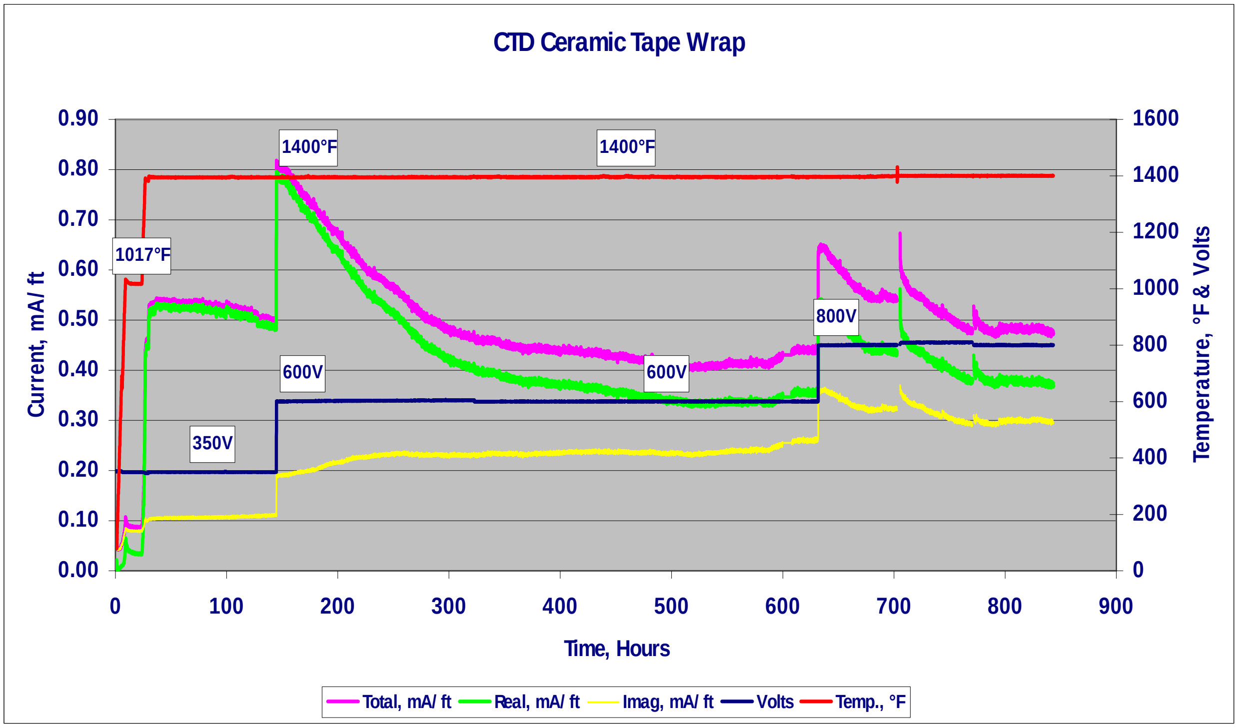

Figure 9. Leakage current performance of a composite insulated heater segment.

It should be noted that similar tests on conventional MI cable resulted in the irreversible dielectric breakdown of the insulation at 760˚C (1400˚F). The breakdown in MI cable is attributed to a phenomenon commonly referred to as “blackening”, and is a result of a high-temperature chemical interaction between the MgO insulation and the steel sheath.

Thus, the results of this testing are a significant step in qualifying these composite-insulated, NANUQ® heaters for use in oil-shale and other oil recovery applications that involve heating underground formations.

Insulation Design and Optimization

In addition to the above testing, the insulation thicknesses required for downhole heaters was modeled to optimize electrical and thermal performance. In these tests, the electrical resistivity of flat-plate specimens was first measured as a function of temperature. Measuring the resistivity (in Ω-cm) provides a means of estimating the effect of leakage current at a given operating voltage. Using this information, a first-order correlation between thickness and heat flow was derived (Fig. 10). This plot was generated using a measured thermal conductivity of 0.5 W/(m·K). Other assumptions for this analysis include a 2.5-cm-diameter central conductor, an applied voltage of 1000 VAC, and a resistivity of 500 MΩ·cm, which is conservative at the 500°C temperature considered. While this is an example for a currently-anticipated operating condition, these analyses could be readily revised to optimize the overall heater performance for alternative situations.

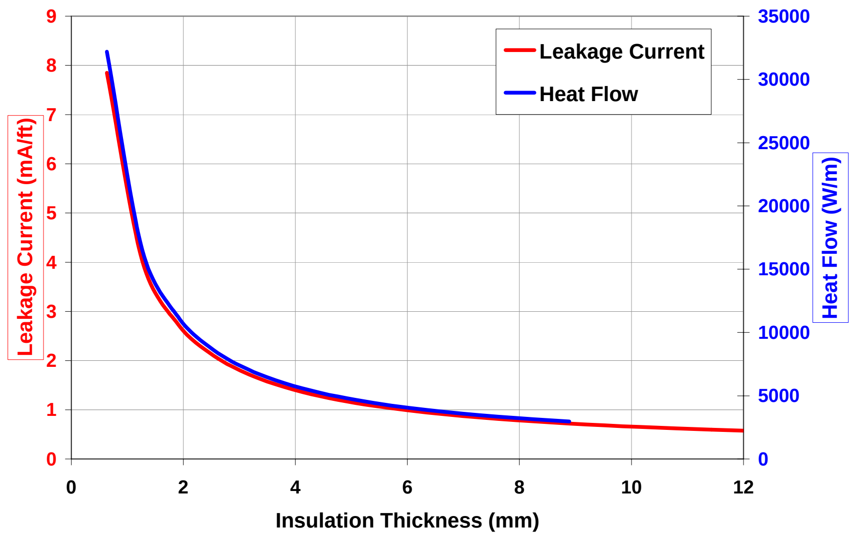

Figure 10. Insulation thickness effect on Heat Flow and Leakage Current.

3.4 Evaluation of Environmental Stability

As previously discussed, one of the limiting factors in the application of MI cables in downhole environments is the moisture sensitivity of the MgO insulation used in those heaters. MgO is a hygroscopic material and its electrical performance degrades quickly when exposed to moisture. Evidence of this is readily apparent in Figure 11, which shows the irreversible failure of a section of an MgO-insulated cartridge heater after only 8 days of exposure to steam. The effects of moisture on the MgO insulation were so dramatic that the stainless steel sheath surrounding the insulation split along its length due to the chemical changes induced by moisture absorption. This rendered the specimen un-testable for this study, and serves as an indication that MgO-insulated heaters would not be reliable for extended operations in the downhole environment.

By contrast, the composite-insulated cables produced by CTD are significantly less affected by moisture. To characterize this aspect of insulation performance, flat-plate composite specimens were exposed to 97% relative humidity environments at 20°C for as long as 6 weeks, and additional parts were immersed in water or exposed to steam. After removal from these high-moisture environments, the specimens were immediately weighed to determine the amount of moisture absorbed by the specimens under each exposure condition [9]. Then they were subjected to electrical tests to verify that the insulation maintained its dielectric strength.

Figure 11. Untested MI cable (below) and specimen after 8 days of steam exposure (above).

Weight measurements performed before and after exposure served as a preliminary indication of the effects of moisture on the insulation. The weights of the green-state specimens were only slightly increased after moisture exposure. As seen in Table 3, green-state specimens exposed to steam and water for 4 weeks picked up a maximum of 13 percent additional mass. These increases were recoverable by heating the parts for less than 4 hours in a convection oven maintained at 100°C.

Specimens that were exposed to moisture in the ceramic state were slightly more susceptible to moisture absorption. The data presented in Table 3 shows that even though the pyrolyzed material absorbed more moisture, it could be readily removed by drying at 100°C for less than 4 hours. Increased weight gain in the ceramic state is an expected trait due to surface porosity in the ceramic structure. This porosity is a result of the polymer-to-ceramic conversion that occurs above 600°C.

Table 3. Summary of weight gained in specimens exposed to steam and complete removal of moisture upon drying (4 hours at 100°C).

Exposure Duration	Green State		Pyrolyzed	
	Exposed	**Dried**	**Exposed**	**Dried**
1 week	8 %	0 %	20 %	0 %
2 weeks	10 %	0 %	22 %	0 %
4 weeks	13 %	0 %	21 %	0 %

Immediately after removal from the moisture environment and weighing (to determine mass gain), a dielectric *withstand* voltage of 2,200 VDC was applied to each specimen at 20°C. This *withstand* voltage value is two times the anticipated operating voltage (600V) plus 1,000V, and this test [10] is used to assess the ability of the insulation to withstand the high applied voltages that are expected upon heat-up after exposure to moisture. At each exposure condition, the green-state 1202 insulation specimens passed the 2,200 VDC withstand test immediately upon removal from the humid (or water or steam) environment. This result shows the capabilities of the 1202 system to withstand moisture during storage, transport, and deployment, while still maintaining its good electrical characteristics.

Withstand testing of ceramic-state insulation was also successful after the material had been dried at 100°C for up to 4 hours. Leakage currents measured during testing of the dried insulation were comparable to the leakage current seen on unexposed test specimens. From these results, the conclusion can be drawn that the impact of moisture on the pyrolyzed 1202 insulation is a temporary effect, caused by containment of moisture within the open structure of the pyrolyzed insulation.

In addition to room-temperature electrical testing, insulation resistance measurements were performed on similar specimens to determine the high-temperature performance of the insulation after exposure to moisture. These tests were performed by uniformly increasing the voltage from zero to 500 VDC over a one-minute period. The 500 VDC potential was then maintained across the specimen thickness as the temperature was increased from room temperature to 650°C at a rate of 1°C per minute, and then returned to room temperature at the same rate.

As shown in Figure 12, both the green- and ceramic-state insulations showed a slightly reduced resistivity upon heating to a maximum temperature of 650°C. The lower resistivity is attributable to the presence of residual moisture in the specimen. However, after reaching the peak temperature any residual moisture was removed from the specimens and the resistivities returned to their original magnitudes. It should also be noted that the green-state specimen is being converted to the ceramic state during this test, whereas both specimens are in the ceramic state during the cooling of the parts. The arrows seen in Figure 7 indicate the heating and cooling for each specimen.

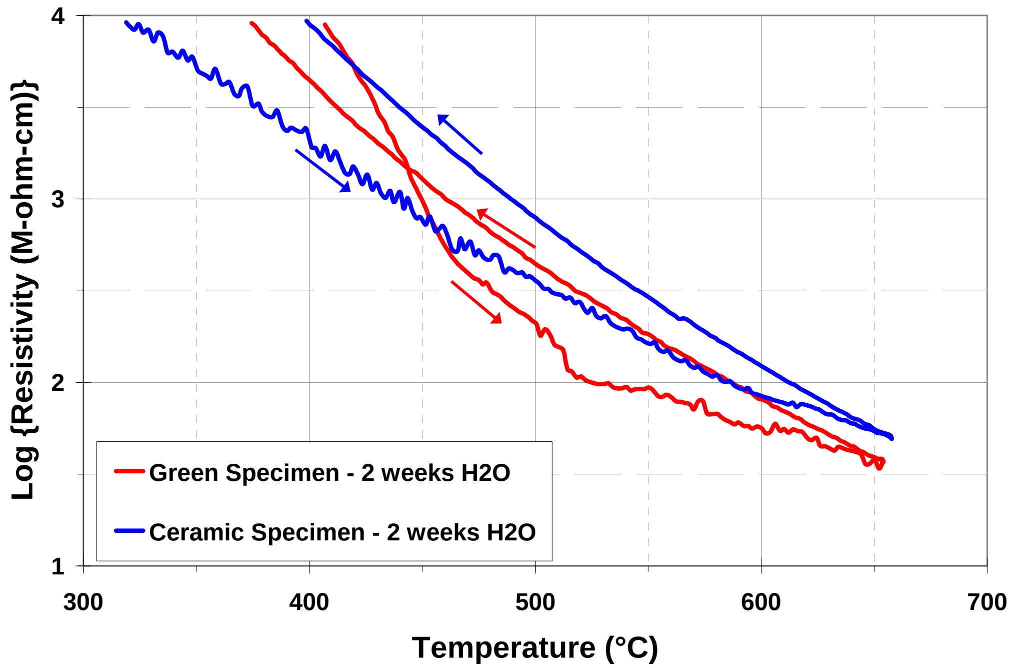

Figure 12. Resistivity plot (log-values) of green- and ceramic-state specimens tested from room temperature to 650°C and then back to room temperature.

In addition to the laminate specimens, integrated heater specimens were also subjected to steam environments for at least 4 weeks. The heater segments used in these tests were similar to those described previously, with a 0.2-cm-thick composite insulation applied to a 30-cm-long center conductor. A 316 stainless steel sheath was applied over the insulation to complete each part. Heater specimens with both green and ceramic insulation were then subjected to the steam environment for at least 4 weeks.

Upon removal from the steam environment, the leakage current of the insulation was measured as the specimens were heated to 700°C. The leakage current and resistivity of the heater segments tested during this reporting period are comparable to previous tests conducted on specimens of similar designs. As seen in Figure 13, the leakage current of the ceramic-state insulation is less than 0.6 mA/ft up to 700°C. Note that data could not be collected below 400°C because the leakage currents were too small to be accurately measured within the test system.

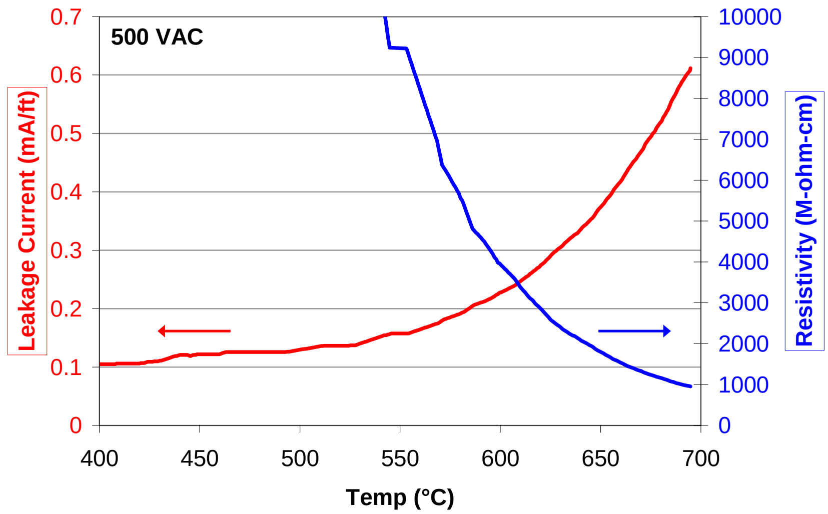

Figure 13. Insulation resistance of pyrolyzed heater specimen exposed to steam for 4 weeks.

These findings are important for oil-shale and other downhole applications because they demonstrate that the composite-insulated heaters developed in this program can reliably withstand exposures to moisture. Steam exposures are expected in downhole environments, and the ability to withstand the effects of moisture is critical for applications requiring long-term operation of electric heaters.

3.5 Intellectual Property

As a result of this SBIR program, CTD has filed two patent applications related to the technology described herein. One of these describes the deployment of heater cables with green-state insulation, and the subsequent conversion to the ceramic state using the heater to initiate this reaction. The second application describes the field-joining of heater cables based on the technology described herein. The authors, title, and application number of the two patents are given below.

- M.W. Hooker, M.W. Stewart, P.E. Fabian, and M.L. Tupper, "In-situ Processing of High-Temperature Electrical Insulation", U.S. Patent Application 20070199709, August 30, 2007.
- M.L. Tupper and C.S. Hazelton, "Field Application of Polymer-Based Electrical Insulation", U.S. Patent Application 20070181306, August 9, 2007.

3.6 Related Applications and Business Opportunities

As work progressed on the development of downhole heaters for oil shale recovery, several other energy-related applications of this technology (or slight modifications thereof) were also identified. These include use in the heating of heavy oil in abandoned or non-productive wells (i.e., Enhanced Oil Recovery, EOR), geothermic fuel cells for hydrocarbon recovery, and cables and other downhole components for geothermal energy production. In each instance the technical requirements for the electrical insulation are similar to those for oil shale applications, and this creates additional opportunities for CTD to provide new technologies for future energy production.

For Enhanced Oil Recovery, heaters are needed to raise the temperature of oil so that it can be pumped to the surface for refining. Quite often less than 50% of the oil present in a well is recovered and the remaining oil can not be reached with currently available tools, so it is left unclaimed. Reliable, high-temperature heaters offer a means of electrically heating the surrounding formations so that so that the previously un-recoverable oil can be extracted using conventional processes. Recovering this oil enables non-functioning wells to be re-opened which saves exploration and drilling costs, while also minimizing the environmental impact of new wells.

Like downhole heaters, Geothermic Fuel Cells (GFC's) are high-temperature systems that have been adapted for hydrocarbon recovery applications. In practice, GFC's would be installed in an array of boreholes drilled into a hydrocarbon resource like coal or oil shale. The fuel cells are preheated and then operated on a start-up, externally-provided fuel like natural gas. After the formation heats up enough to begin producing fuel gases on its own, the fuel cells are switched over to fuel coming from the target deposit, and at that point the fuel cells become self-sustaining. As the underground formation is heated, valuable gases and liquids are driven into collection wells drilled and pumped to the surface. Once fully operational, the fuel cell also generates excess electricity which could be used to provide power for surface activities.

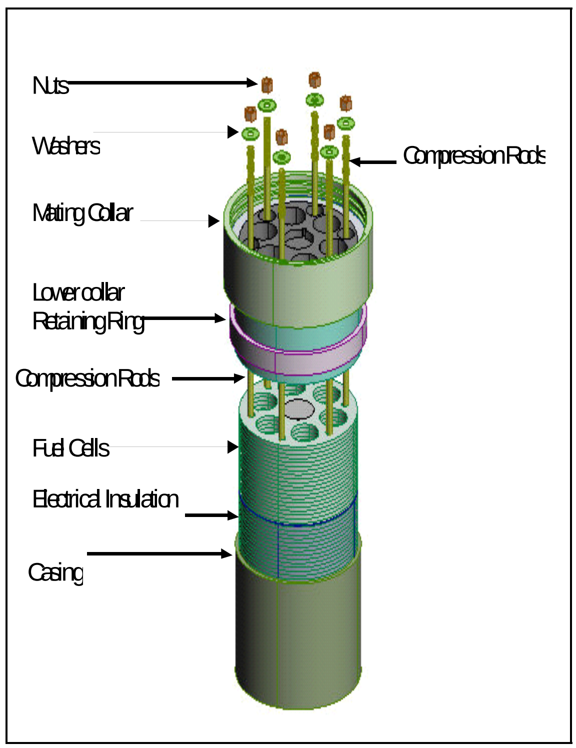

Figure 14. Geothermic Fuel Cell.

The high-temperature electrical insulation technology developed in this SBIR program is currently being considered for use in GFC's. As seen in Figure 14, the insulation would be applied between the fuel cells and the outer casing of the assembly, and would provide electrical isolation of the fuel cells over the lifetime of the devices.

The third application of this technology currently under evaluation involves use in Geothermal energy. Geothermal reservoirs are a renewable energy resource that can be harnessed either to produce power for "direct use" purposes, or to supply energy to the nation's power grid. The shallower wells operate at a lower ambient temperature (120 to 150°C) and are utilized in "direct-use" applications, whereas deeper geothermal reservoirs have a higher ambient temperature (150 - 230°C) and are used for electrical power generation.

Utility-scale electric power is produced by drilling wells into geothermal reservoirs containing hot water and steam, and pumping the high temperature fluid to the surface where it is used to turn turbine generators to produce electricity (See Figure 15). As these higher-temperature geothermal reservoirs are quite deep (sometimes in excess of 2 miles), it is often necessary to employ artificial lift technology to raise the geothermal fluid to the surface for use in electric power generation.

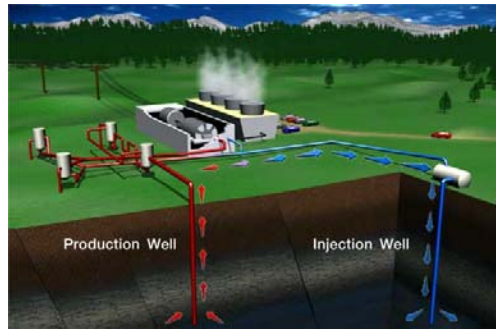

Figure 15. Geothermal power plant.

The artificial lift system used for this purpose is called an electric submersible pump (ESP). The electric motors in ESP systems require voltages up to 5kV, and that power is generally provided by variable frequency drive (VFD) power supplies located above ground. This electric feed power is supplied to an electric induction motor located inside the geothermal reservoir by means of insulated conductors called ESP cables. Two types of ESP cables are used in a high temperature ESP well completion; standard ESP cables and motor lead extension cables (connects the electric motor to the bulk ESP cable). The electric induction motor, in turn, operates multiple centrifugal pump stages to provide artificial lift of the geothermal fluid.

CTD recently began two new projects related to geothermal energy production. One of these is a Phase I SBIR that involves the development of high-temperature-compatible ESP cables. These cables must operate for extended periods of time in high-humidity environments at temperatures up to 300˚C, so the NANUQ™ technology developed in this current Phase II establishes a strong basis for this work to be successful. Additionally, CTD was recently awarded a DOE program that will involve the development of high-temperature motor windings that will enable the downhole deployment of ESP pumps. Operating these pumps at elevated temperatures will enable more efficient geothermal energy production. CTD is working with a key industry leader in both of these programs to ensure the rapid commercialization of these technologies.

4 Conclusions

Over the course of this DOE SBIR program, CTD developed and demonstrated NANUQ™ downhole heaters based on a ceramic-composite electrical insulation system. The basis of this technology is a continuous-fiber-reinforced, pre-ceramic-polymer insulation that can be readily applied to the heater elements using industrially-scalable, prepreg-based manufacturing processes. After applying the insulation to the conductor, the inorganic-polymer composite is converted to a ceramic-matrix composite by heating the material to at least 500˚C. Upon conversion to the ceramic-state, the composite insulation was found to exhibit a stable electrical performance after 5,000 hours of high-temperature, high-voltage testing. Alternatively, conventional MI cables were found to have an irreversible dielectric breakdown (i.e., an electric short between the conductor and sheath) under these conditions. This finding is significant because MI cables were initially considered for use in this application due to their relatively good high-temperature performance compared to other heater-cable technologies.

In addition to its high-temperature performance, CTD's NANUQ™ heaters also have significantly improved resistance to moisture as compared to MI cable insulations. This is particularly important for oil and gas applications because the heaters will be subjected to steam in the downhole environment. Because MgO is a hydroscopic material, the insulation in MI cables can absorb water and cause the performance of the cable to quickly degrade. Alternatively, the composite insulation used in this work was found to be resistant to moisture even after direct, long-term exposure to steam.

Finally, CTD is considering other energy-related applications of this technology. This includes potential use in Enhanced Oil Recovery, Geothermic Fuel Cells, and Geothermal energy production. Reliable, moisture-resistant insulation is an enabling technology for each of these applications, and the ceramic-based insulations described in this report offer a unique combination of properties that were not previously available within the industry. All are currently being evaluated for near-term use.

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